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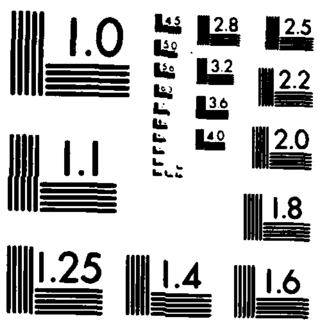
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Fabry-Perot Interference Filters

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The discrimination of coherent, laser radiation from incoherent, white-light radiation can be accomplished with properly designed interference filters that make use of the coherent nature of laser radiation in addition to its narrow-band spectral character. In this study it is assumed that we wish to block high power laser radiation from a detector without impeding its ability to "see" light emitted by broad-band, incoherent, weak continuum sources. We analyse two types of Fabry-Perot, air spaced

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filters: 1) the tunable two- or multiplate Fabry-Perot interferometer and 2) a multiplate stack of 1/4-wave plates. It is shown that the Fabry-Perot interferometer has a limited rejection ratio for coherent radiation, but offers the possibility of a relatively large tuning range. By contrast, the rejection ratio for coherent radiation of quarter-wave plates can be made as large as 10^5 with a white-light transmission of 20%, and a bandwidth $\Delta\lambda/\lambda_0 = 0.03$. However, the tuning range of such a stack will be limited.

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FABRY-PEROT INTERFERENCE FILTERS

Air-spaced Fabry-Perot (FP) interferometers allow one to discriminate narrow-band, monochromatic, coherent radiation from wide-band, incoherent, white light radiation. Used as filters they offer a number of advantages over other interference filters. Foremost is their tunability and high spectral resolution. In addition they are simple, rugged, relatively immune to high energy radiation, have large apertures, large throughputs, and tolerate large angles of incidence. Properly designed they have a contrast ratio of near 100 in discriminating laser radiation from white light sources.

In general a Fabry-Perot filter consists of a pair of flat, transparent plates separated by a gap of width d. The plates are coated with reflection coatings of reflectivity R on their insides, and with anti-reflection coatings on their outsides. Radiation enters the FP through one plate and exits through the other.

Such an interferometer will transmit coherent radiation of wavelength λ_0 at all places in the spectrum where[1]

$$\frac{2nd}{q} \cos \theta = \lambda_0 \tag{1}$$

Here n is the refractive index of the gas between the plates, θ is the angle of incidence of the incoming radiation, and q = 1, 2, 3, 4 ... are the orders of interference. This equation shows that by changing d or n the filter can be tuned to transmit the coherent radiation at $\lambda = \lambda_0$. All other radiation, which is either incoherent or is coherent but does not coincide with the resonances of the filter, is reflected back at the source. The FP filter allows us, therefore, to discriminate white light sources from coherent

sources as, for example, lasers. The proper use of the FP interferometer is, therefore, as a reflection filter that will reflect incoherent light and pass coherent radiation.

The resonances of the various orders of the interferometer are separated from each other in wavelength by the free spectral range of the interferometer $(\Delta\lambda)_{FSR}$ given by[1] (for $\theta=0$, $n=1$)

$$(\Delta\lambda)_{FSR} = \lambda_0/q = \lambda_0^2/2d \tag{2}$$

Each resonance has a bandwidth (FWHM) of $(\delta\lambda)_{BW}$ depending on the reflectivity R of the plates[1]:

$$(\delta\lambda)_{BW} = \frac{\lambda_0(1 - R)}{q\ \pi\ R^{1/2}} = \frac{\lambda_0^2(1 - R)}{2\ d\ \pi\ R^{1/2}} \tag{3}$$

These equations show that by making the plate separation d large, or what is the same, by making the order of interference q large, many, very narrow transmission resonances can be generated covering the transmission band of the coatings of the interferometer. It is also seen that the bandwidth of the resonances goes to zero as the reflectivity R of the coatings approaches 1. As an example let $R = 0.8$, $d = 1$ cm, $\lambda_0 = 4$ µm then $(\Delta\lambda)_{FSR} = 8.0 \times 10^{-4}$ µm and $(\delta\lambda)_{BW} = 5.7 \times 10^{-5}$ µm. Typical laser lines (DF laser with $\lambda_0 = 4$ µm) have a line width (laser modes) of $\Delta\lambda_{LM} = 5.3 \times 10^{-7}$ µm with the modes covering a wavelength region (DF Doppler line width) of $\Delta\lambda_{DL} = 1.6 \times 10^{-5}$ µm. It can be seen that if the transmission of the FP filter could be made large at $\lambda = \lambda_0$ a large fraction of the laser radiation would pass the filter and would, therefore, be eliminated from the incoherent radiation reflected into the incoherent detector.

The contrast ratio C for discriminating incoherent from coherent radiation in the light reflected from the FP filter will be defined as

$$C = \frac{R_{inc}}{R_{coh}} \tag{4}$$

where R_{coh} is the reflection coefficient of the FP for coherent radiation at $\lambda = \lambda_0$, the wavelength of the laser, and R_{inc} is the reflection coefficient for incoherent radiation.

The transmission coefficient for coherent radiation at $\lambda = \lambda_0$, the peak of the FP transmission band, is[1]

$$T_{coh} = \left(1 - \frac{A}{1-R}\right)^2 \tag{5}$$

so that the coherent reflection coefficient is given by

$$R_{coh} = 1 - T_{coh} = 1 - \left(1 - \frac{A}{1-R}\right)^2 \tag{6}$$

Here A is the absorption coefficient of the FP reflection coatings. For very good dielectric coatings $A = 2 \times 10^{-3}$.[2]

The reflection coefficient for incoherent, white light of a Fabry-Perot of high reflectivity, i.e., when reflections from the second plate can be neglected, is simply $R_{inc} = R$. In the more general case, including one reflection from the second plate, it can be shown

$$R_{inc} = R(1 + (1 - R)^2) \tag{7}$$

so that finally

$$C = \frac{R(1 + (1 - R)^2)}{1 - [1 - A/(1 - R)]^2} \tag{8}$$

This function has a maximum for R = 0.40

$$C_{max} = \frac{0.54}{1 - (1 - 1.67\ A)^2} \tag{9}$$

which for A << 1 becomes approximately

$$C_{max} \approx 0.163/A \tag{10}$$

For $A = 2 \times 10^{-3}$ the contrast ratio reaches a maximum of $C_{max} = 82$, the highest value achievable with good reflection coatings.

Assuming again a laser line at $\lambda_0 = 4.0$ µm, d = 1 cm, and optimum reflection coatings, one finds a free spectral range $(\Delta\lambda)_{BW} = 2.42 \times 10^{-4}$ for this contrast-optimized FP filter. The "DF-laser line" at 4 µm would therefore be adequately covered by this FP, and 99.3% of the incident laser radiation would pass the interferometer reflecting only 0.66%. At the same time 54% of the incident incoherent radiation would be reflected by the FP.

To tune the FP to the laser line at $\lambda = \lambda_0$, it would be sufficient to bring one of the many resonances into agreement with the laser wavelength, i.e., the FP has to be tuned at most by half a free spectral range. If this tuning were done by changing the separation d between the plates, then d will have to be changed by a distance Δd:

$$\Delta d = \frac{q(\Delta\lambda)_{FSR}}{4} = \lambda_0/4 = 1\ \mu m \quad \text{at } \lambda_0 = 4\ \mu m$$

which is easily accomplished with the aid of a piezo-electric transducer in times of the order of 10 msec.

It has been suggested that a FP interferometer in the transmission mode be used as a fast blocking shutter for a relatively wide-band detector filter and that this could be achieved by making the plate separation d very small. To pass, e.g., a 0.4 μm band through a FP interferometer at 4 μm the plate separation d has to be

$$d = 6.4 \times 10^{-4} (1-R)/R^{1/2} \mathrm{cm}$$

For all reasonable values of R = 0(1) d will be of the order of 10 μm, or of the dimensions of unavoidable dirt on the plates. It will simply be impossible to move the plates so close to each other. A slight relaxation of this condition can be achieved by using two interferometers in series that are detuned with respect to each other so that their common transmission bandwidth becomes twice that of a single FP. The improvement is only a factor of two at best, achieved at the expense of a reduced incoherent transmission.

Much better discrimination in a transmission Fabry-Perot interferometer filter can be obtained by using quarter-wave plate stacks.[3] In this interferometer a number N of plates of index of refraction n and thickness t are separated by air spaces of width d. The plates are not coated, which makes this interferometer largely immune to high power radiation. The thickness t of the plates is chosen such that $nt = q\ \lambda/4$ where q = 1, 3, 5, ... Likewise, the air spaces are adjusted to make the optical path $d = q\ \lambda/4$. Interference of coherent radiation takes place both inside the plates and inside the air spaces, so that this FP is only marginally tunable. The interference inside the plates and gaps is, however, now destructive, so that the stack is

transparent for incoherent radiation and blocks coherent laser radiation at all frequencies where

$$\lambda = 4n\ t/q$$

The transmission coefficient for coherent radiation at the peak of one of the resonances is given by[3]

$$T_{coh} = 1 - \left(\frac{1 - n^{2N}}{1 + n^{2N}}\right)^2$$

and for incoherent radiation

$$T_{inc} = \left[1 - \left(\frac{n - 1}{n + 2}\right)^2\right]^N$$

so that the contrast ratio C for discriminating coherent from incoherent radiation in transmission is

$$C = \frac{T_{inc}}{T_{coh}}$$

Table 1 gives values of C and T_{inc} for a number of IR transmitting materials as a function of the number N of plates in the stack.

Table 1. Contrast Ratio and Transmission of 1/4-Wave Stacks

	n = 1.5		ZnSe n = 2.4		Si n = 3.5		Ge n = 4.1	
N	C	T_{inc}	C	T_{inc}	C	T_{inc}	C	T_{inc}
2	1.67	0.92	6.1	0.69	18.2	0.48	28.3	0.40
3	3.0	0.89	27.6	0.57	152	0.33	298	0.89
4	5.9	0.85	131	0.48	1290	0.23	3160	0.16
5	12.2	0.82	626	0.40	9000	0.16		
6	25.8	0.78	2990	0.33				
8	119	0.72	68500	0.23				
10	553	0.67						

It is seen that very high rejection ratios can be obtained at relatively high incoherent transmission. It is also obvious that a much larger number of plates is required, if materials of low refractive index are used. However, stacks of low index plates exhibit higher incoherent transmission coefficients for the same contrast ratio and are, therefore, preferable from this point of view.

The bandwidth of the rejection resonances of the filter is given by [3]

$$(\delta\lambda)_{BW} = \frac{4\lambda}{\pi(2N - 1)} \sin^{-1} \left(\frac{1 - n}{1 + n}\right)$$

and their separation, i.e., their free spectral range, by

$$(\Delta\lambda)_{FSR} = \frac{\lambda^2}{4nt}$$

The free spectral range depends only on the thickness of the plates and their refractive index, whereas the width of the reflection maximum decreases with increasing number of plates. The bandwidth also decreases with decreasing index of refraction n, as can be seen from Table 2, which lists relative bandwidths for the materials of Table 1 and various stacks.

Table 2. Bandwidth $(\delta\lambda/\lambda_0)_{BW}$ of 1/4-Wave Stacks

		ZnSe	Si	Ge
N	n=1.5	n=2.4	n=3.5	n=4.1
2	0.086	0.18	0.25	0.28
3	0.051	0.11	0.15	0.17
4	0.037	0.077	0.11	0.12
5	0.029	0.060	0.082	
6	0.024	0.049		
8	0.017	0.036		
10	0.014			

The expressions presented here for the transmission of quarter-wave stacks as a function of wavelength apply only to the transmission at the resonance peaks. There are a number of secondary resonances spaced between the major peaks for which the coherent transmission is reduced but to a smaller degree only. The full wavelength dependent transmission coefficient of this type of FP has to be calculated from the complete interference theory.

It should also be stressed again that interferences, and therefore filter rejection, occur only for radiation with a coherence length

$$\ell_{coh} = (\Delta\lambda)_{source}/2\pi \gg t,d$$

where $(\Delta\lambda)_{source}$ is the line width of the source radiation. For white light and any radiation for which $\ell_{coh} \ll t,d$ no transmission or rejection maxima occur, and the transmission of the filter is uniform in wavelength over the entire spectral transmission range of the materials used for its construction.[4]

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